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ELECTRON MICROBEAM TESTING OF INTEGRATED CIRCUITS

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ABSTRACT

The ever decreasing size and increasing complexity of electronic microcircuitry implies the need for new testing methods for circuits too small for the use of mechanical probes, and too complex for functional testing limited to input and output terminals. This paper considers the feasibility of various methods of using electron beams to introduce signals and sense potentials at arbitrary points in a microcircuit. These techniques, which are compatible with electron and ion beam fabrication processes, are capable of providing multiple inputs and outputs with currents close to one microampere in one micron size spots. It is shown that circuit potentials may be accurately determined using either mirror microscopy or secondary electron energy distributions. The techniques should make very large arrays of very small components practical by allowing in situ discretionary wiring to proceed concurrently with testing.

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INTRODUCTION

Driven by the advantages of lower cost, increased reliability, reduced weight, and greater packing density, the size of electronic circuitry has rapidly been reduced. Subject to constraints imposed by power dissipation, circuit impedence and other device limitations, and the constraints imposed by the fabrication and testing technology, this trend is likely to continue. The increased complexity at reduced cost, which appears to be a fundamental result of small component size, may be expected to produce wide new applications for electronic circuitry.

In order to make further size reduction practical, many problems must be solved. While electron and ion induced reactions have been shown to permit fabrication techniques with resolution limits far better than those activated by light, much further work will be required before this technology comes into general use.[1-24] It is also clear that present testing techniques will be inadequate if component size is significantly reduced.[25,26] It is the purpose of this paper to propose new testing methods, based on the technology of charged particle optics, which are suitable for testing very large arrays of ultra-miniature components.

LIMITATIONS ON PRESENT TESTING TECHNIQUES

Production testing of microcircuits is currently performed mechanically by contact with the pads intended for bonding the circuit to its header. While this method is completely suitable for testing simple and

relatively large thin-film microcircuits, several difficulties hinder its use with more complex circuits composed of ultra-miniature components:

1. The number of contact pads currently provided for input and output is not sufficient for efficient testing of complex networks. Consider for example an LSI array composed of 100 binary elements; assume these elements to be connected in some arbitrary way. To test this circuit as a system, using its inputs and outputs, requires testing a large fraction of the system states, and in the worst case the circuit may have up to 2^{100} ($\simeq 10^{30}$) system states. Obviously performing such a number of tests is not practical. If the individual elements and interconnections were tested separately however, only a few hundred (10^2 to 10^3) tests would be required. To make such tests however it would be necessary to inject test voltages and currents directly into the circuit, as well as to sense both voltages and currents within the circuit. Since it does not appear to be possible to build mechanical testers or probes capable of probing the interior of a microcircuit, particularly if component size is significantly reduced, new testing methods must be found.

2. Contact pads are presently on the order of 100μ or larger in diameter, thus the total number of contacts is limited to the order of several dozen at most. As circuitry decreases in size many more input and output connections will probably be desired, forcing a reduction in contact pad size. If these contacts are to be used for mechanical test probes as well as final wiring, it is difficult to see how their size can be reduced by even one order of magnitude.

3. As the number of components becomes large, the problem of reliability becomes acute if a circuit is to be rejected for only one (or a few) defects. While it is possible (and often desirable) to use

redundancy to improve reliability, the use of discretionary wiring provides a much higher yield without increasing the number of components. In addition, discretionary wiring allows the fabrication of circuits for many different functions, using only one set of basic circuits which can be deposited in a single master pattern. This latter advantage becomes particularly significant with LSI arrays which require very complicated patterns. Unfortunately, the present mechanical testing techniques and the present thin film interconnecting methods require very different apparatus and environments; testing takes place under an optical microscope, while interconnections are made in high vacuum. Because of this incompatibility, the two processes cannot proceed concurrently; hence the present attempts at discretionary wiring have been complex, limited in flexibility, and to a large extent economically unsuccessful. A testing technique which is compatible with discretionary wiring, to allow wiring, testing, and rewiring to proceed in an arbitrary way, would possess substantial advantage.

These difficulties strongly suggest searching for other means of testing circuits which are more easily scaled to small size, more amenable for use with large scale arrays, and which are compatible with some sort of discretionary wiring scheme. Since it is probable that microcircuits will be fabricated using electron and ion beams within a few years (because of improved resolution and flexibility), it seems natural to try to use charged particle optics (CPO) to perform this testing. Particle beams, and electron beams in particular, have already been used for a substantial amount of microcircuit testing. Beams have frequently been used to inspect microcircuits using scanning electron microscopes, mirror microscopes, and X-ray microprobes. These techniques are useful

and well developed.[27-36] Thus far however, their use has been limited to indirect testing, that is testing which observes structures and voltages in the circuit but makes no attempt to introduce either signals or structural changes directly by means of the beam.

DESIGN CONSIDERATIONS AND POTENTIAL ADVANTAGES OF CPO TESTING

Several potential methods of building active CPO testing systems, in which multiple signals could be directly injected into the circuit with simultaneous observation of circuit potentials and discretionary wiring capability, were considered. These include systems utilizing both electrons, ions and photons, systems which utilize both high and low accelerating voltages, systems with scanning single-beam optics, multi-beam optics, image optics and parallel optical channels. All these methods are necessarily much more complicated than the simple introduction of test signals by means of a mechanical contact. In effect they can be viewed as a means of buying more reliable and more sophisticated microcircuitry at the expense of greatly increased tester complexity.

Though many possible systems could be made to work, one basic idea, the use of electron beams in a multi-beam geometry at electron energies in the neighborhood of 10 KeV, seems superior to all others considered. The study is obviously not complete (a good fraction of the best ideas are always missed). The reasons for the choice of an electron multibeam geometry are developed below.

Active CPO testing is subject to several fundamental limits as well as numerous engineering problems. Among the decisions to be made in designing such a system are

(1) The choice of the type of charged particle to be used. While

electrons are by far the easiest to generate and control, both electrons and ions have strong advantages and disadvantages.

(2) The choice of an optical system to deliver the current where required, and the choice of appropriate particle energy. Problems concerning perveance, brightness, power dissipation, breakdown, surface contamination, and secondary particles, must all be considered.

(3) The choice of a method for accurately measuring circuit voltages, (voltages resulting either from injected currents or from operation of the microcircuitry). If it is desired to introduce voltage signals into the circuit, target voltage information must be used in a feedback loop in order to make the beam look like a voltage source (normally such a beam looks like a current source). Sensing voltages would also appear to be the only practical way of obtaining outputs from the interior of a microcircuit.

(4) Choice of a method to uniquely identify various beams and currents, if several beams are to be used simultaneously.

(5) Choice of techniques for discretionary wiring, which are compatible with the energies, current densities, and particle types used to make tests.

(6) Choice of techniques to suppress effects (when necessary) such as surface contamination, secondary emission, excessive power dissipation, unwanted sputtering, unwanted carrier injection at junctions, and unwanted ion implantation.

(7) The choice of component type, size, and current level, to be compatible with CPO fabrication, testing, and discretionary wiring techniques. Limitations due to charged particle optics may well determine the types of components which can be used, when component size decreases below that compatible with mechanical or light optical techniques.

VOLTAGE, CURRENT AND SPOT SIZE

Several fundamental well-known relationships limit the current, given an accelerating voltage and spot size, for a charged particle beam bombarding a material surface.[37-40] For the present application it is desired to obtain the maximum current with minimum power dissipation and minimum undesirable side effects. These constraints, plus a knowledge of what constitutes a minimum satisfactory beam current, imply the choice of particle and particle energy. Some of these limits are graphed in Figures 1 through 6, where beam current and current density are shown as a function of accelerating voltage for six different spot sizes.

An important limitation on maximum current is set by space charge.[37] This limit, usually expressed as a perveance (current/voltage$^{3/2}$), is independent of absolute beam size for congruent beam shapes. For long thin electron beams it is usually set by the cathode geometry, and usually lies in the neighborhood of 1 μperv, however this value may be improved by a factor of 2 or 3 by careful cathode design. In principle, much more substantial improvement could be made by using space charge neutralization, but in practice, stabilization of the neutralizing charge is hard to obtain. At very low voltages the perveance limit may be overcome by using grided apertures; unfortunately at higher energies the grids are destroyed by beam heating. A perveance limit corresponding to 1 μperv has been plotted in each of the graphs.

A second (and for small spot size, more important) limitation on beam current is set by the brightness of the electron source.[38,41,42] The second law of Thermodynamics implies that the intrinsic brightness associated with the flux of any type of particle can never be increased. For electrons in the case where the beam energy is much greater than the

temperature characterizing the source energy spread, this limit results in a maximum current of;

$$i_{max} = \frac{3\pi^2}{16} B_o \left[\left(\frac{eV}{kT} \right) \frac{d^{8/3}}{C_s^{2/3}} \right] \text{ amperes} \qquad (1)$$

Here B_o is the brightness of the cathode (A/cm^2/steradian), V is the beam energy (volts), T is the cathode temperature (°K) (or the temperature associated with the characteristic source energy spread), d is the beam spot diameter (cm), and C_s is the spherical abberation constant of the most critical lens (cm). For a convenient and easily obtainable electron source (for example a tungsten hairpin operating at about 3000°K) with a brightness of 1 amp/cm^2/steriadian, and using an objective lens with a spherical aberration constant of 1 cm (corresponding to a quite good magnetic lens), the maximum current as a function of beam size and voltage becomes

$$i_{max} = [1.46 \times 10^{-10} \text{ V (volts) } d^{8/3} \text{ } (\mu)] \text{ amperes} \qquad (2)$$

where d has been converted to microns for convenience. This limit has also been plotted. Note that the brightness limit is markedly dependent on beam size, in contrast to the perveance limit which is not. Also note that it is perveance which controls maximum current in large spot electron beam melters or welders, whereas brightness sets the limit in the case of virtually any type of electron microscope, and the CPO tester under consideration here. The brightness limit may be relaxed from that shown by at least one to two orders of magnitude by use of special electron sources.[43-52] Such sources are not yet in widespread use however, largely because of problems with stability; these problems will probably be overcome.

Two limitations result from the bombardment of a microcircuit lead or pad surface by high energy electrons: First the bombarding particles should come to rest within the pad, otherwise the signal is not introduced to the pad but where the electrons come to rest (if electrons penetrate the pad and enter the semiconductor substrate hole-electron pairs will be created). Second, most of the electron kinetic energy ends up as heat in the pad, and the resulting temperature rise may be detrimental to the operation of the circuit.

The range of electrons and solids has been well studied, and a variety of formulas for calculating various effective ranges in different energy ranges exist.[53] One suitable for present purposes is

$$R = 3.5 \times 10^3 \left(\frac{V \text{ (volts)}}{10^6} \right)^{7/4} \mu \qquad (3)$$

where a target density of 2.3 gm/cm^3 (silicon) has been assumed. This equation effectively sets the required pad thickness. Note that the accelerating voltage should not be so large as to result in a range larger than the spot diameter since this corresponds to a hemisphere of scattered electrons inside the target larger than the spot diameter. Because the diameter of this hemisphere corresponds to the effective diameter of the beam (as far as the circuit is concerned), one might just as well have used a larger incident beam, and obtained more current. Lines showing the voltage at which electron range becomes comparable with the spot diameter are plotted in each graph.

Accurate calculation of temperature rise in a test pad is very difficult,[54-57] but a simple estimate is sufficient to guarantee that the rise does not exceed some nominal value. Assume that the total beam power is dissipated uniformly as heat in a hemisphere centered at the surface;

assume further that the diameter of this hemisphere is equal to either the beam diameter or the electron range, whichever is greater. Direct calculation for the case in which the range is less than the beam diameter (the well-known disc heating model gives essentially this result) shows that

$$\Delta T = \frac{3}{2}\left(\frac{VI}{\pi dK}\right) \ ^\circ K \tag{4}$$

Here K is the thermal conductivity (watts/cm°K), which is approximately 1 for silicon. Thus if an allowable temperature rise were 10°K, the maximum allowable current would be

$$I = 2.1 \times 10^{-3} \ \frac{d(\mu)}{V(\text{volts})} \quad \text{amperes} \tag{5}$$

where the diameter has again been converted to microns and a thermal conductivity of unity has been assumed. Note that the allowable current is inversely proportional to voltage (for constant power). The corresponding calculation for the case of range greater than beam diameter yields a limit

$$I = 7.3 \times 10^{-6} \left(\frac{V(\text{volts})}{10^6}\right)^{3/4} \quad \text{amperes} \tag{6}$$

where the allowable current now actually increases with voltage because the energy is dissipated over a larger volume. (This latter case is not of much interest of course, for the reasons already given.) The limit on current expressed by Eqs. 5 and 6 has also been plotted.

Note that these equations are very approximate; Eq. 4 may be conservative by a factor of as much as 5 due to electron back scattering and other effects described by Wells. On the other hand no allowance has been made for the fact that the circuit may be bombarded by several beams simultaneously, which means that the semi-infinite solid approximation is

not very valid. In addition, uniform isotropic heat conductivity has been assumed for the chip, and clearly this is not realistic. Lastly the calculation assumes a steady beam. If testing were accomplished using short pulses (which is natural for a digital circuit) and if testing could be completed in a small fraction of a second, much higher power densities could be tolerated.

It may now be seen from the graphs that for a 1 micron spot (a particularly suitable size for microcircuit testing) that the limit on current is determined basically by the limitations of electron brightness and electron range, while the temperature rise places another restriction at essentially the same level. The most appropriate beam energy to run for maximum current would appear to be 5 to 10 kilovolts.

It is worthwhile to consider the appearance these graphs would assume if ions rather than electrons had been used. Several fundamental differences may be seen. The perveance limits for ions is more restrictive than for electrons because the allowable current depends inversely on the square root of the particle mass. Thus for monatomic Hydrogen the allowable current is down by a factor of 43, for Argon it is down by a factor of 270, etc. The perveance limit is again the important one when designing high-energy, large diameter beams.

The intrinsic brightness of an ion source depends markedly on the means of producing ionization, which in turn depends upon the type of ion. Hence it is difficult to make general statements. Unfortunately however, the types of ion sources which do have high intrinsic brightness tend to be either very limited as to the types of ions they can accelerate (for example surface ionization types), or depend upon high intensity gas discharges (which generate large gas loads).

The power density limit for ion beams is the same as that for an electron beam, except that the ion range is approximately two orders of magnitude shorter for the same energy. Thus much higher energies may be used without penetrating the contact pad. Two other new effects however, implantation and sputtering, must be considered. The current densities obtainable on the 1μ graph (Fig. 3) for example would, if ions were used, sputter right through a 1μ thick pad in a few milliseconds.

SENSING CIRCUIT POTENTIALS

Given that it is possible to inject sufficient current into a contact pad for microcircuit testing purposes, the other crucial element necessary for success is the ability to obtain output signals from the circuit. There are several possible ways of achieving this.

In the simplest case the output circuitry might be already wired in, since a great deal of information can be obtained about the operation of the circuit by the introduction of test signals at points other than the input. This method has several disadvantages however. First, it is obviously more flexible to read out signals at any point in the circuit. Second, while it may be possible to provide power connections to the circuit (that is one voltage supply and ground), it would be difficult to provide multiple output leads to circuitry which is still in the fabrication state (i.e., many chips in a large wafer). Third, the ability to measure potentials anywhere in the microcircuit greatly facilitates the introduction of voltage test signals, since the point at which the beam current is injected may be monitored and the information used to control the beam current. If this is not possible, the test voltage must be inferred from the test current and a knowledge of circuit impedence, and unfortunately the circuit impedence may not be known. In some cases even the actual net beam current into the test pad may be hard to determine.

Potentials within the circuit may be determined using charged particle optics in either of two general methods. The potentials may be sensed by their effect on charged particles moving close to the surface, as in an electron mirror microscope. Or alternatively, the potentials may be sensed by observing the energy spectrum of charged particles emitted from the surface. Mirror microscopy has the advantage of displaying potentials for an entire circuit all at once (and thus making faults easy for a human observer to see), however a relatively complicated image-to-test-point converter would be required to utilize this information in an automatic system. The charged-particle emission method can avoid this difficulty, but requires some mechanism to make the circuit emit particles. Such emission however can be achieved in a large variety of ways.

Electron and/or ion emission can be induced from any surface by the bombardment of photons, ions, or electrons (or even fast neutrals), and by the application of heat or high electric fields. The energy spectra of all these emitted particles contains information which may be used to determine surface potentials to within a fraction of a volt. Since the circuit is already being bombarded with electrons as a means of test current injection, it seems a natural choice to use the secondary electrons resulting from this bombardment to determine surface potentials (in a manner similar to that frequently used in scanning electron microscopes).

A very large amount of experimental work on secondary electron emission has been done.[58-64] Typical curves for the secondary electron yield of a metal and the energy spectrum of these electrons are shown in Fig. 7. Note several features. At high primary energies (necessary to obtain the required current), the yield is usually less than one, i.e., the number of secondary electrons emitted is less than the number of bombarding electrons.

Also, the secondary electrons may be roughly divided into two groups: elasticly reflected primaries along with primaries which have undergone small characteristic energy losses, and true secondaries which have up to a few tens of volts energy. Since the minimum kinetic energy a secondary electron can have is zero energy at the emitting surface, the distribution cuts off very sharply at this point. What is needed is a method of sensing the position of this cutoff, or even better, a method to produce a current or voltage signal linearly proportional to the surface potential. One possible method would be to accelerate all secondary electrons through a small fixed potential, and then pass them through a parallel plane energy analyzer equipped with an area collector. The area collector would be designed to collect all electrons with energies below a specified value, and the output current would then be a monotonicly increasing function of pad voltage, provided that voltage always remains within a reasonable voltage (5 volts perhaps) of ground.

In monitoring several surface potentials simultaneously by use of secondary electron spectra, a means of correlating spectra with the various individual pads is required. Since the test points are very close together the secondary currents from all of them will easily pass through the same secondary electron analyzer; in fact the entire microcircuit, because of its size, will act essentially as a point source for the analyzer. Perhaps the simplest way to separate and identify the secondary currents coming from various pads would be to add a low level amplitude modulation signal with a characteristic frequency to the beam hitting each pad. If this modulation was limited to a few per cent, the microcircuit (particularly digital circuits) would ignore it, but the energy analyzer could identify secondary electrons by means of characteristic frequencies. A diagram of

one possible arrangement of such a system is shown in Fig. 8. An important limitation on such a system would be the bandwidth with which digital information can be injected or extracted on each beam. While transit time spreads for beam electrons are very short (if appropriate modulating structures are provided, beams could carry information in the gigacycle range), sensing target potentials at high frequency seems out of the question. First, the secondary currents will be small (perhaps 10^{-8}A); second, modulation frequencies are limited by signal-to-noise and the obvious constraint that there must be many electrons in each cycle of each tracer signal; third; the detector output electronics will be severely limited in its frequency response by the output filter or synchronous detector used to detect modulation. It may be necessary to inject high frequency signals using only one channel at a time, or alternatively, to use the beam information only to activate transistor gates while high frequency signals are injected by means of one (or a few) trunk signal wires.

OTHER TECHNIQUES

Another mechanism for obtaining pad voltage readout would be to use an electron mirror microscope along with a multiple microbeam array for injecting currents. By taking electrical readouts directly from the mirror microscope image, very high bandwidth could be achieved. Unfortunately however, the electrostatic objective lens required for a mirror microscope seems incompatible with the short focal length lens required for high energy microbeams. A possible way to overcome this conflict might be to work on the microcircuit from both sides; microbeam inputs on one side and mirror microscope outputs on the other. This method of course would require very thin circuit chips (which would be difficult and perhaps impractical from the microcircuit point of view).

One other method of injecting multiple signals which does not require the use of modulation should perhaps be mentioned. Channel electron multipliers can now be manufactured with diameters down to a few microns,[65-72] and such multipliers could be used to communicate directly with a microcircuit. Indeed, these multipliers could be used to communicate both ways with a microcircuit, since the channels are small enough to be able to focus their entire output on a single pad. At present this method does not seem as attractive as those already discussed because of problems of recovery time (due to discharging of the dynode structure), limits on output current due to space charge, and the energy spread of electrons at the anode end (which makes focusing at a distance difficult). Some of these limitations might be removed by designing new channel multipliers with this use in mind. The method would have the advantage of requiring no real electron optics, while the power dissipation in the circuit is reduced since the final electrons have energies of only one to two hundred volts. Note that some MOS semiconductor circuitry can respond to charges on the order of 10^{-11} to 10^{-12} Coulombs, while a channel multiplier can provide over 2×10^{7} electrons per pulse (3.2×10^{-12} Coulombs), and that while repitition rates are low the pulses themselves can be very fast. Channel multipliers might also be used in large arrays to make a large area cathode which could convert a light signal into an electron signal with moderate brightness.

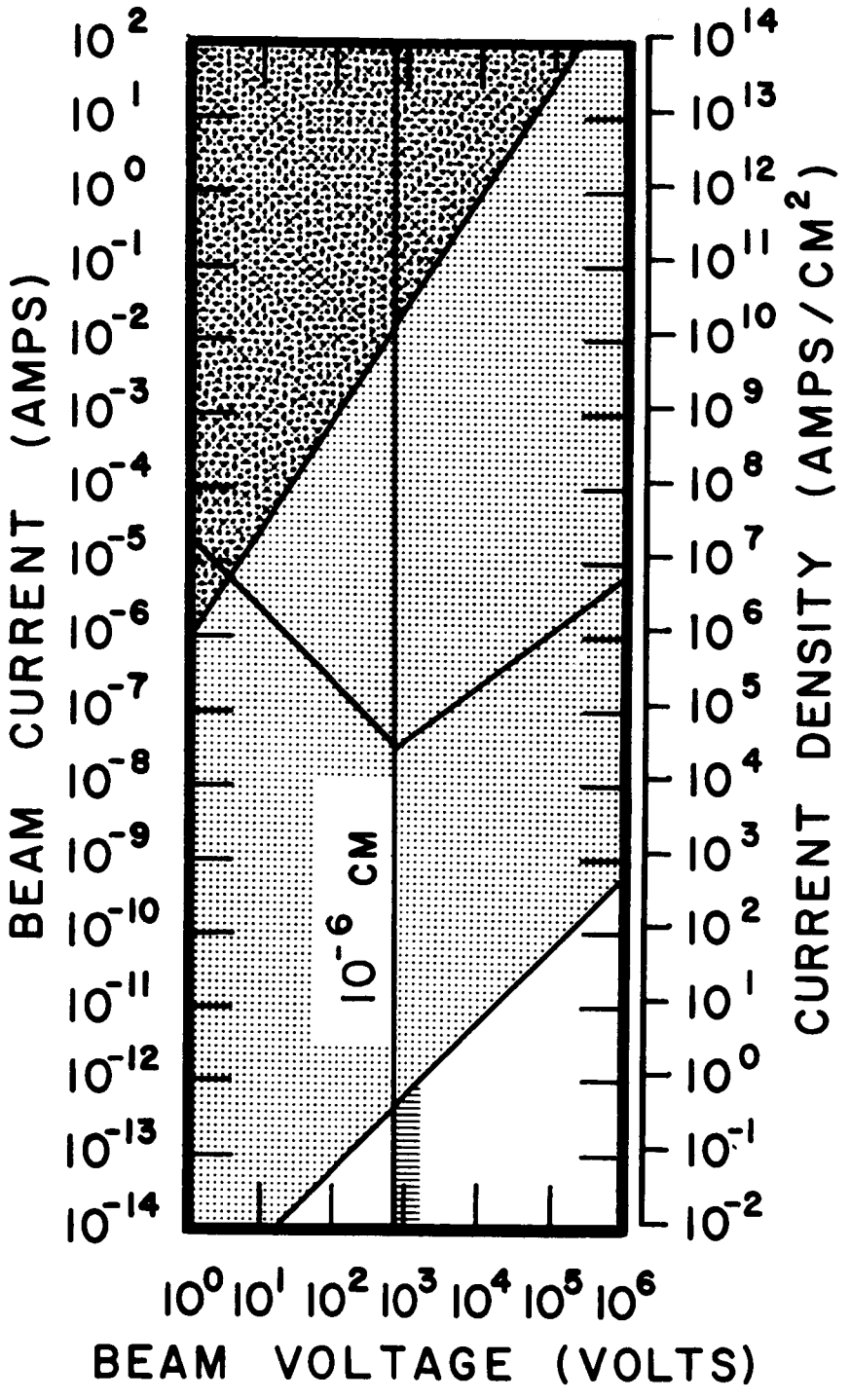

Fig. 1. Limitation on electron beam current and current density as a function of beam voltage for a 100 Å (10^{-6} cm) spot size. The heavily shaded region at the upper left represents perveance values greater than 1 μperv. The lightly shaded region corresponds to brightness values greater than 1 A/cm^2/steradian. The vertical line dividing the graph roughly in half shows the voltage for which electron range is equal to 100 Å in silicon, while an approximate 10°C temperature rise line (again for silicon) intersects the range limit line in the center of the diagram.

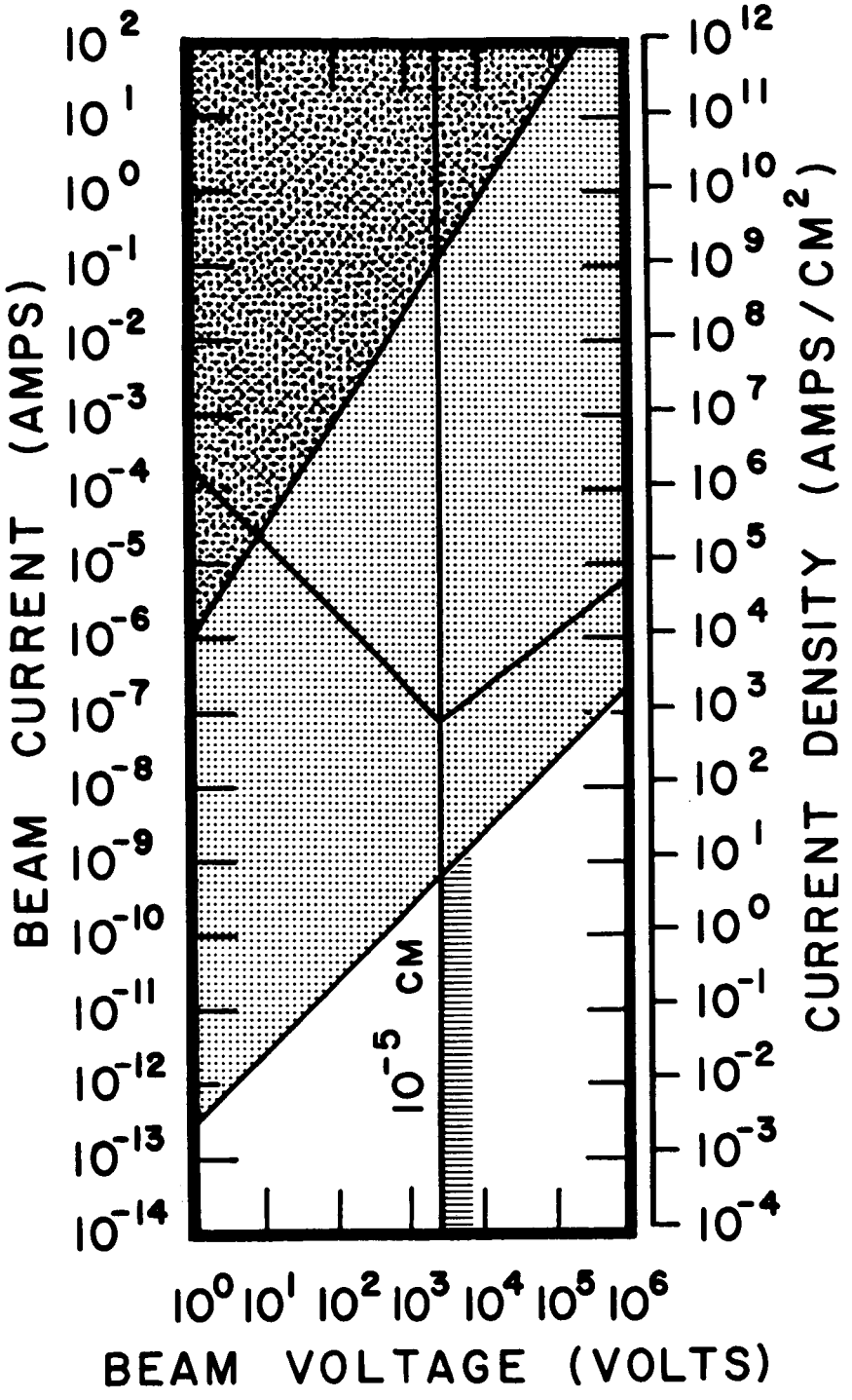

Fig. 2. Limitations on beam current and current density as a function of beam voltage for a 1,000 Å (10^{-5} cm) spot size. Note that the perveance limit has not moved, but that the brightness limit has been relaxed by more than two orders of magnitude.

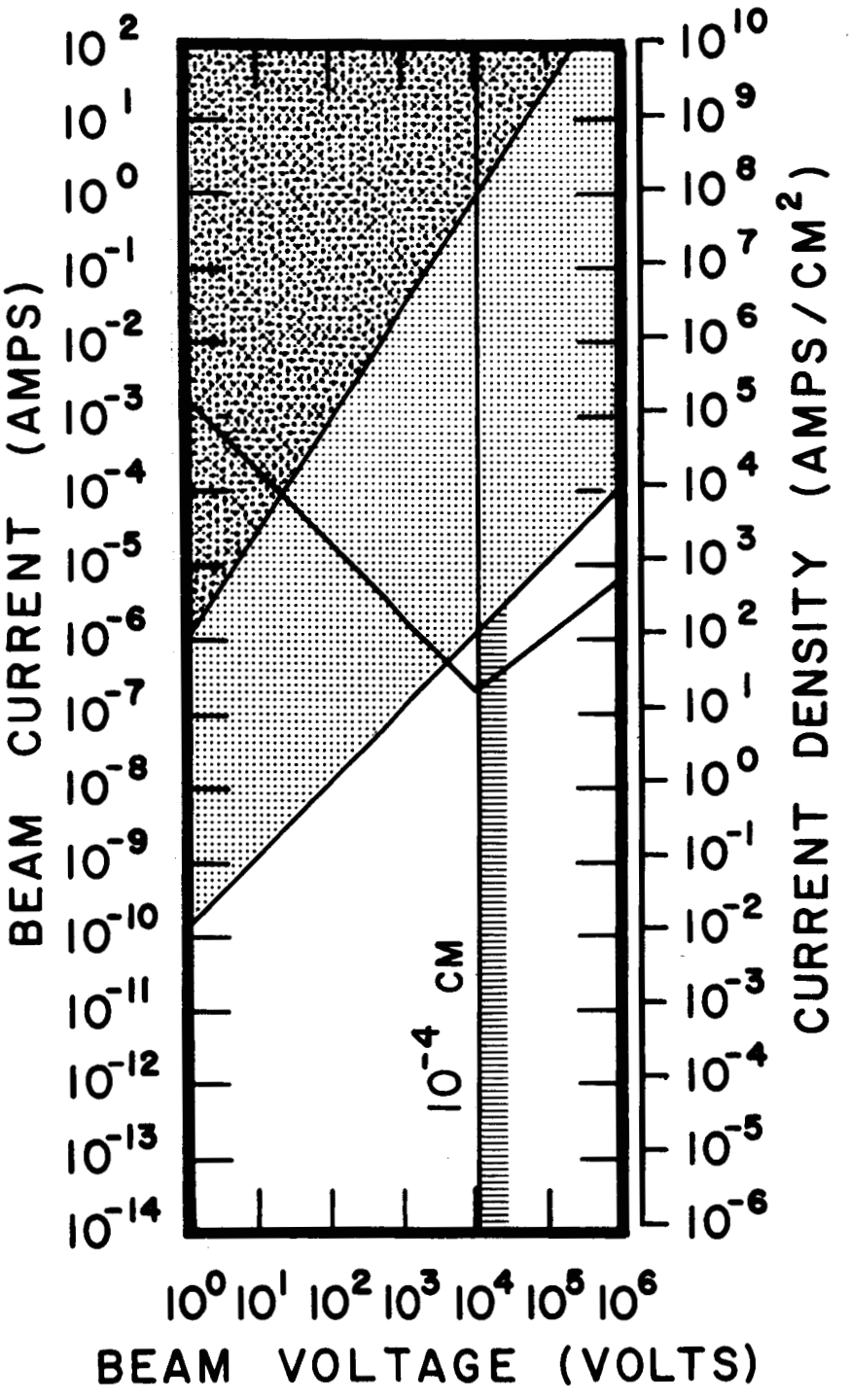

Fig. 3. Limitations on beam current and current density for a 1 micron (10^{-4} cm) spot size. For a temperature rise not much greater than 10°C, one microampere total currents and 100 amperes per cm^2 are obtainable in the neighborhood of 1 to 10 kilovolts.

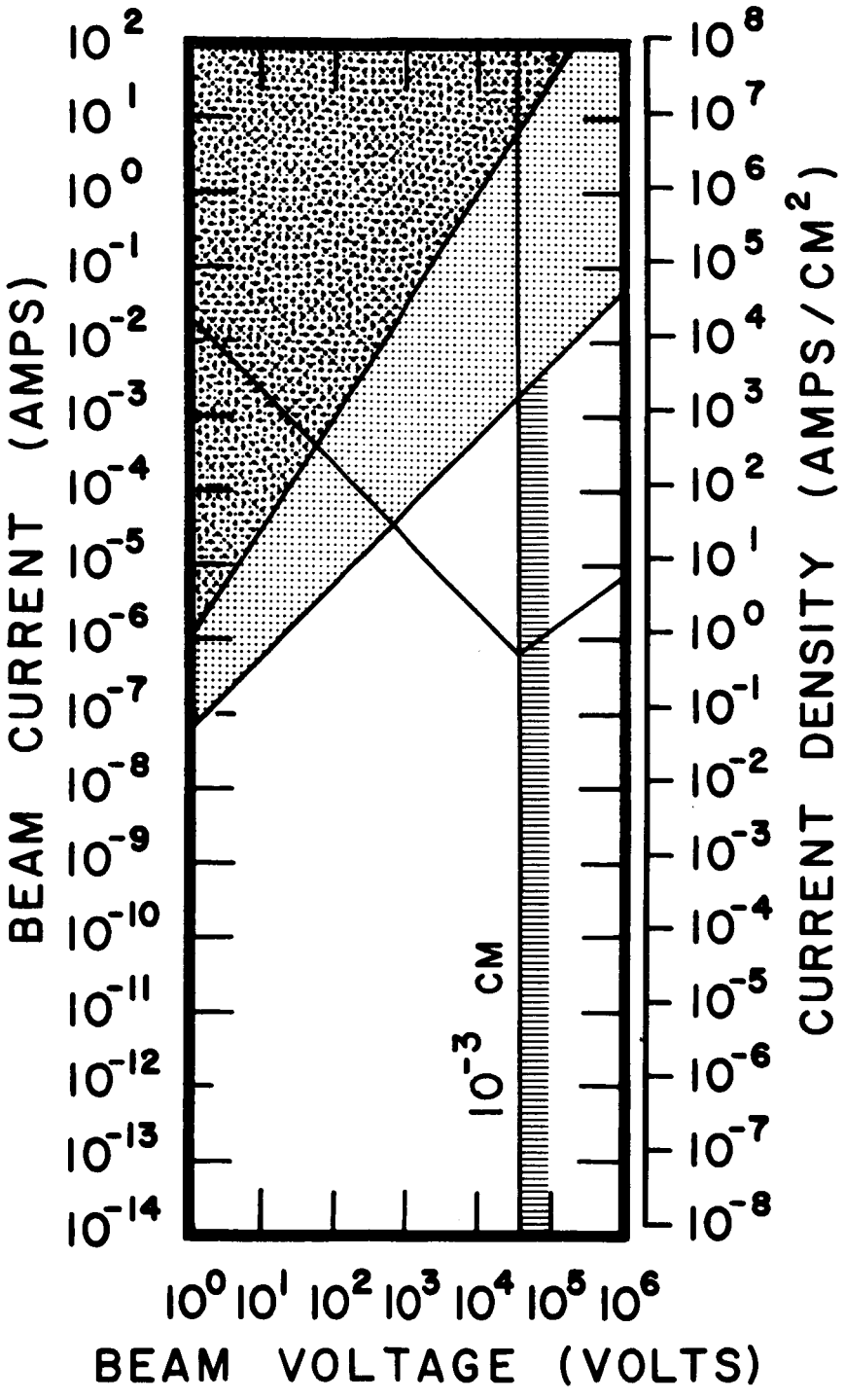

Fig. 4. Limitations on beam current and current density for a 10 micron (10^{-3} cm) spot size. Note that allowable brightness and range at high voltage correspond to a substantial surface temperature rise.

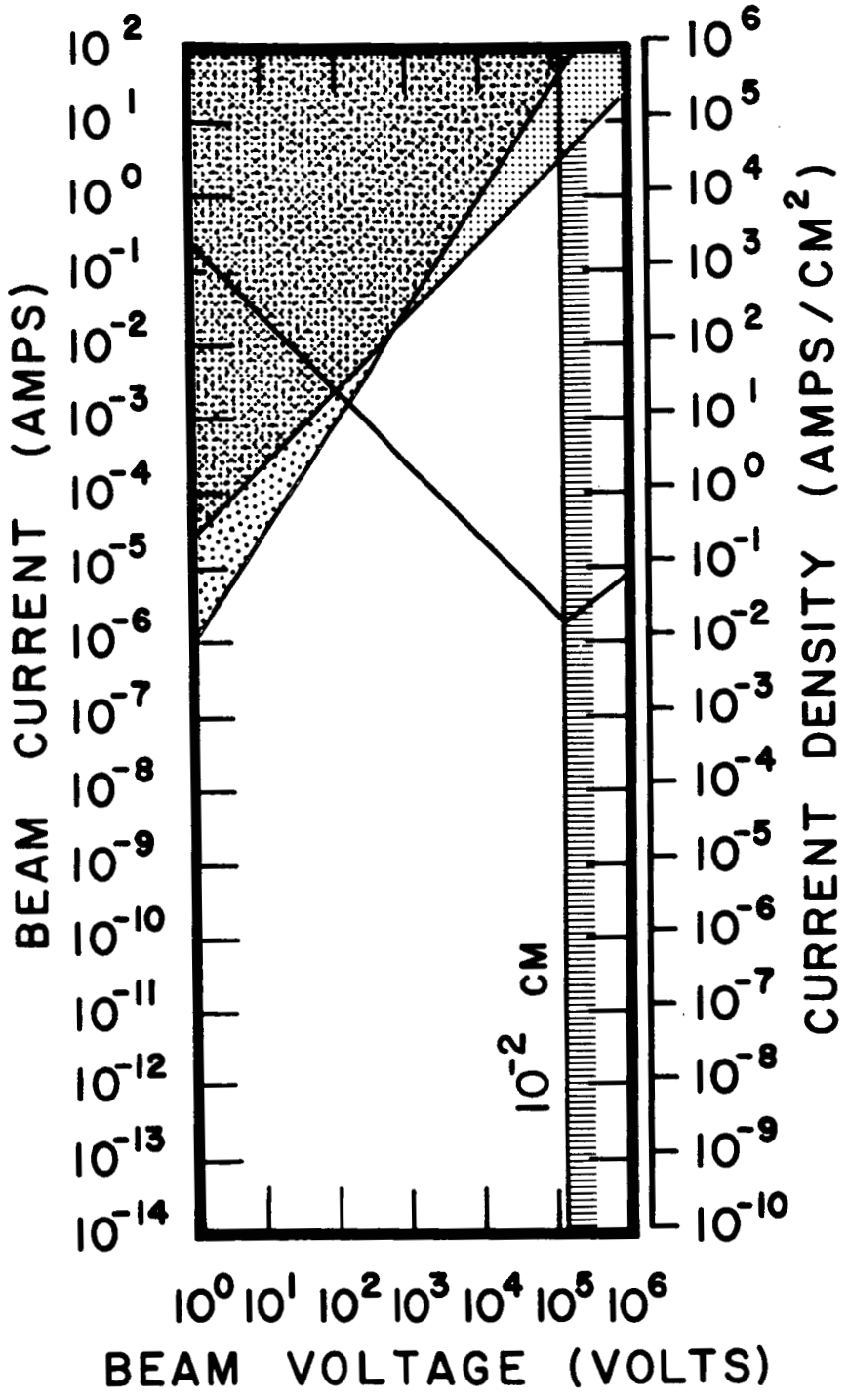

Fig. 5. Limitations on beam current and current density as a function of beam voltage for a 100 micron (10^{-2} cm) spot size. The brightness limit has now relaxed to the point where it is comparable to the perveance limit.

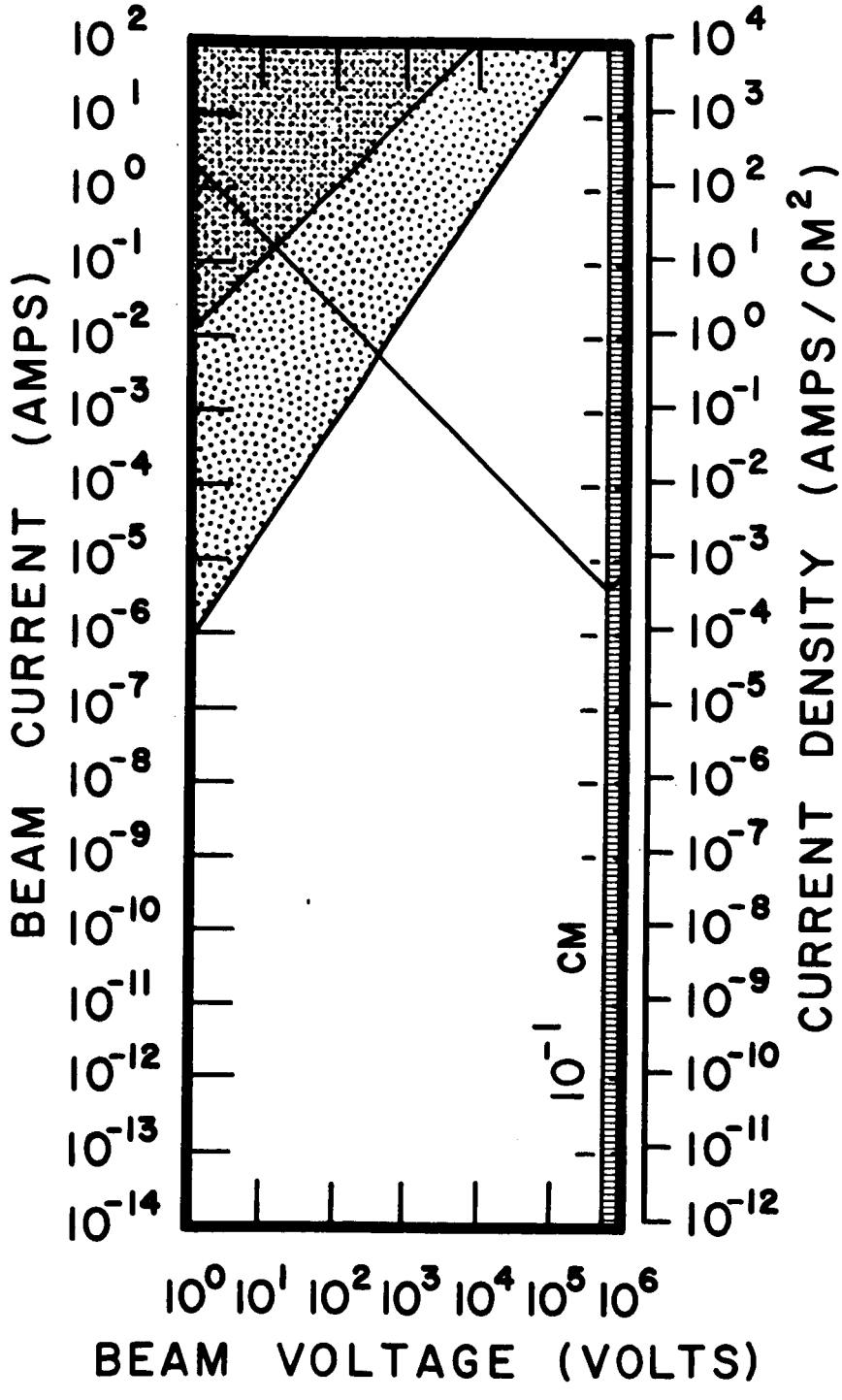

Fig. 6. Limitations on beam current and current density as a function of beam voltage for a 1,000 micron (10^{-1} cm) spot size. The limitation on beam current is now provided entirely by perveance.

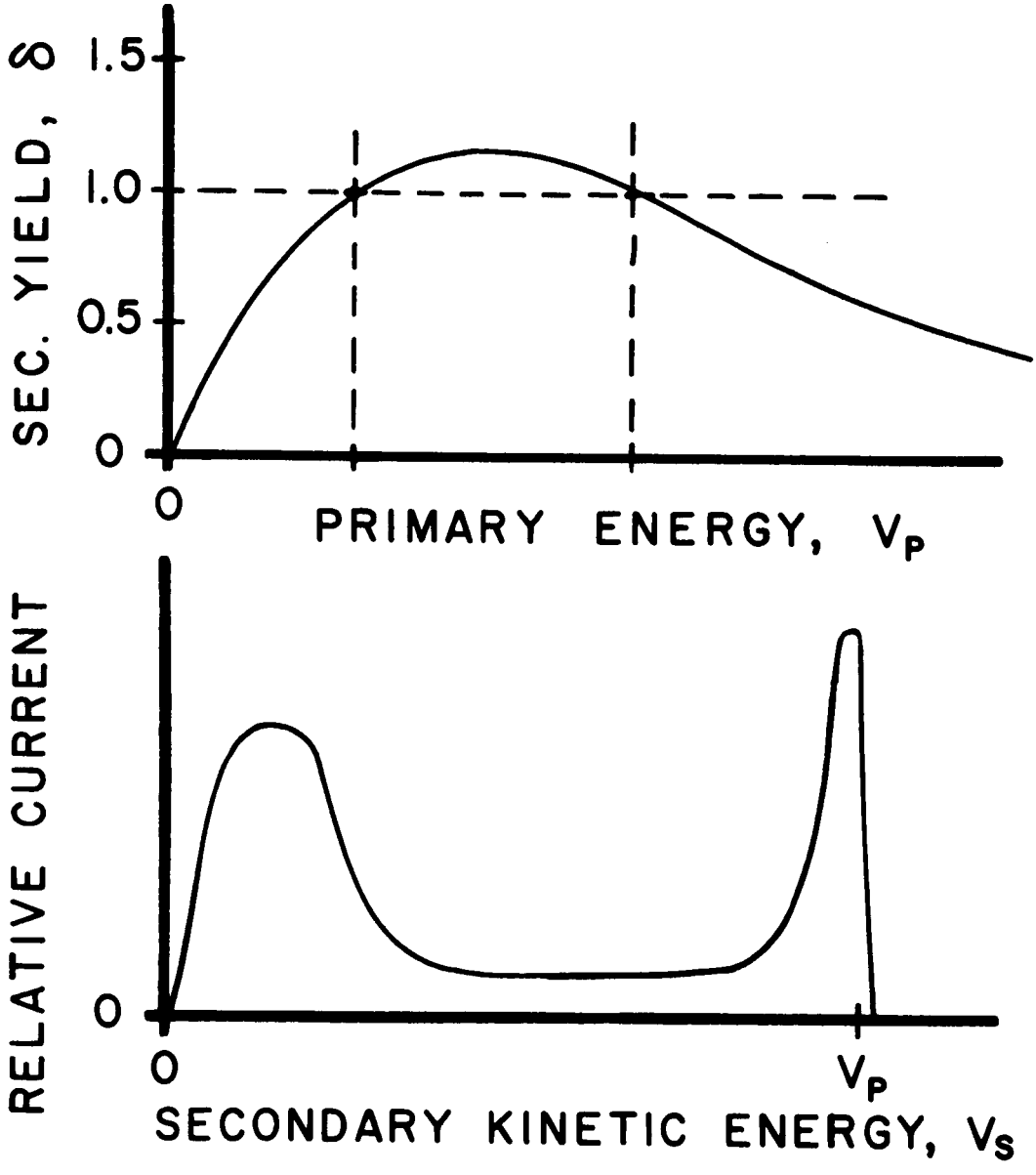

Fig. 7. Secondary electron yield as a function of primary electron energy and relative secondary current as a function of the kinetic energy of the secondary electrons. The narrow peak near V_p is due to reflected primaries, the broad peak near zero kinetic energy results from true secondary electrons.

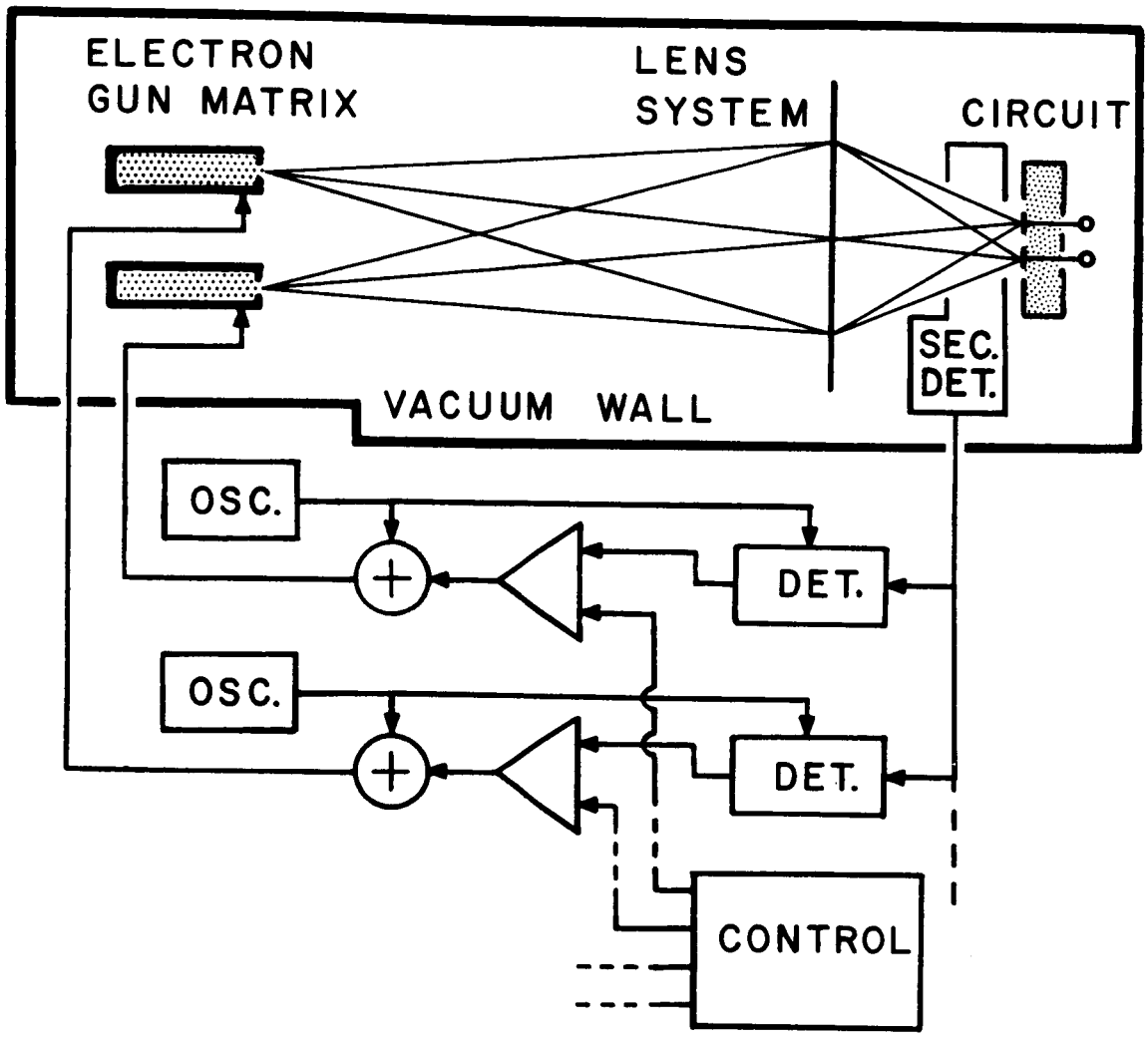

Fig. 8. Proposed multi-beam electron gun geometry equipped with a potential sensor based on secondary electron emission. The secondary detector performs an energy analysis on all secondary electrons, while the resulting signal is separated into components associated with each separate target by a synchronous detector keyed to each electron gun. The system can be set up to inject either voltage or current signals and simultaneously sense voltage outputs at predetermined points in the microcircuit. A magnetic short focal length lens system must be used if current levels up to those shown in Fig. 3 are desired.

REFERENCES

1) D.A. Buck and K.R. Shoulders, "An Approach to Microminature Printed Systems", Special Publication T-114, Proc. Eastern Joint Computer Conf., (December 1958).

2) R.W. Christy, "Formation of Thin Polymer Films by Electron Bombardment", J. Appl. Phys. 31, 1680 (1960).

3) A.G. Baker and W.C. Morris, "Deposition of Metallic Films by Electron Impact Decomposition of Organometallic Vapors", Rev. Sci. Instr. 32, 458 (1961).

4) C.K. Crawford, "Electron Beam Machining", in Introduction to Electron Beam Technology, R. Bakish, Editor, Wiley, 1962, pp. 315-353.

5) G. Mollenstedt and R. Jonsson, "Elektronen-Mehrfachinterferenzen an regelmaßig hergestellten Feinspalten", Zeit. Physik., 155, 472 (1959).

6) G. Mollenstedt and R. Speidel, "Elektronenoptischer Mikroschreiber unter Elektronenmikroskopischer Arbeitskontrolle", Physikalische Blatter, 4, 192 (1960).

7) K.R. Shoulders, "Research in Microelectronics Using Electron-Beam-Activated Machining Techniques", Stanford Research Institute, 1960.

8) M.W. Larkin and R.K. Matta, "The Electron Beam Fabrication of Small Geometry Transistors", Scientific Paper 66-9F1-SCFAB-P1, Westinghouse Research Laboratories, October 18, 1966.

9) T.W. O'Keeffe and R.M. Handy, "Resistless Fabrication of Integrated Circuits", Technical Program, International Electron Devices Meeting, October 18-20, 1967.

10) M. Hatzakis, "Electron Resists for Microcircuit Fabrication", Technical Program, International Electron Devices Meeting, October 18-20, 1967.

11) K.T. Rogers, J. Kelly, D.L. Cogswell and E.R. Westerberg, "Submicron, Electron Beam Addressed Storage Structures and Associated Electron Optics", Technical Program, International Electron Devices Meeting, October 18-20, 1967.

12) J. Ling, "An Approximate Expression for the Growth Rate of Surface Contamination on Electron Microscope Specimens", Brit. J. Appl. Phys. 17, 565 (1966).

13) J.M. Hlavin and R.A. Fotland, "The Fabrication of Electronic Components" in First International Conference on Electron and Ion Beam Science and Technology, R. Bakish, Editor, Wiley, 1965, pp. 231-244.

14) T.E. Everhart, "Nonthermal Electron-Beam Recording" in First International Conference on Electron and Ion Beam Science and Technology, R. Bakish, Editor, Wiley, 1965, pp. 341-351.

15) P.W. White and D.W. North, "An Electron-Beam Memory Utilizing Some Properties of Polymer Films" in First International Conference on Electron and Ion Beam Science and Technology, R. Bakish, Editor, Wiley, 1965, pp. 352-364.

16) R.K. Matta, "High-Resolution Electron-Beam Exposure of Photoresists", Electrochemical Technology, 5 382 (1967).

17) K.R. Geddes, "Equilibrium Potentials of Isolated Metal Areas During Electron Beam Bombardment Polymerization", Microelectronics and Reliability 6, 17 (1967).

18) B.A. Vishnyakov and K.A. Osipov, "Investigation of the Deposition of Molybdenum Carbide Films from Molybdenum Hexacarbonyl Using an Electron Beam", Sov. Phys. - Solid State 8, 2976 (1967).

19) C.J. Varker and E.M. Juleff, "Electron Beam Recording in SiO_2 with Direct Read-Out Using the Electron Beam Induced Current at a p-n Junction", Proc. of the IEEE 55, 728 (1967).

20) I.W. Drummond and J.V.P. Long, "Scanning Ion Microscopy and Ion Beam Micro-machining", Nature 215, 950 (1967).

21) C. Jech, "Ion-Bombardment Enhanced Solubility in Solids", Phys. Stat. Sol. 21, 481 (1967).

22) B.A. Vishnyakov and K.A. Osipov, "Obtaining Thin Films of Molybdenum Carbide from Molybdenum Hexacarbonyl Under the Action of an Electron Beam", Sov. Phys. - Solid State 9, 1216 (1967).

23) K. Kanaya and H. Yamazaki, "Measurement of Spot Size and Current Density Distribution of Electron Probes by Using Electron Beam Exposure of Kodak Photoresist Films", Optik 25, 471 (1967).

24) K. Kanaya, K. Tanaka and T. Yuasa, "The Electron Beam Exposure of Photoresist and Electron Beam Processing Capabilities" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 281-282.

25) L. Steckler, "IC's - to test...or not to test?", Electronics Products 10, 19 (1967).

26) A.R. Strube, "LSI for High-Performance Logic Applications", Technical Program, International Electron Devices Meeting, October 18-20, 1967.

27) P.K. Thornton, K.A. Hughes, Htin Kyaw, C. Millward and D.U. Sulway, "Failure analysis of Microcircuitry by Scanning Electron Microscopy", Microelectronics and Reliability 6, 9 (1967).

28) T.E. Everhart, A.J. Gonzales, P.H. Hoff and N.C. MacDonald, "Applications of the Scanning Electron Microscope to Semiconductor Devices", in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 201-202.

29) S. Kimoto, H. Hashimoto and M. Sato, "On a Scanning Electron Microscope" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 197-198.

30) G.V. Saparin, G.V. Spivak and S.S. Stepanov, "Observation of the p-n Junction at Small Constant and Alternating Bias with the Scanning Electron Microscope" in Sixth Internation Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 609-610.

31) T.H.P. Chang and W.C. Nixon, "Scanning Electron Microscopy and Electron Beam Effects on Silicon Surfaces" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 193-194.

32) H. Kimura, H. Higuchi, H. Tamura and M. Maki, "New Scanning Electron Microscope and its Applications" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 195-196.

33) A.E. Lukianov and G.V. Spivak, "Electron Mirror Microscopy of Transient Phenomena in Semiconductor Diodes" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 611-612.

34) N.F.B. Neve, K.A. Hughes and P.R. Thornton, "Scanning Electron Microscope as a Means of Studying Microplasmas at High Resolution", J. Appl. Phys. 37, 1704 (1966).

35) T.E. Everhart, O.C. Wells and S. Matta, "Evaluation of Passivated Integrated Circuits Using the Scanning Electron Microscope", J. Electrochem. Soc. 111, 929 (1964).

36) C.W. Oatley and T.E. Everhart, "The Examination of p-n Junctions with the Scanning Electron Microscope", J. Electron. Control 2, 568 (1957).

37) J.R. Pierce, Theory and Design of Electron Beams, D. Van Nostrand Company, Inc. 1954.

38) V.K. Zworkin, G.A. Morton, E.G. Ramberg, J. Hillier and A.W. Vance, Electron Optics and the Electron Microscope, Wiley, 1945.

39) P. Grivet, Electron Optics, Pergamon Press, 1965.

40) O. Klemperer, Electron Optics, Cambridge University Press, 1953.

41) R.E. Oglivie, "Electron Beams in Microanalysis", in Introduction to Electron Technology, R. Bakish, Editor, Wiley, 1962.

42) D.B. Langmuir, "Theoretical Limitations of Cathode-Ray Tubes", Proc. I.R.E. 25, 977 (1937).

43) H. Fernandez-Moran, "Applications of Improved Point Cathode Sources to High Resolution Electron Microscopy" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 27-28.

44) S. Maruse and K. Hara, "Uber die Bedingungen fur einen Erfolgreichen Gebrauch der Spitzenkathode", Memoirs of the Faculty of Engineering, Nagoya University 9, 330 (1957).

45) H. Shimoyama, A. Oshita and S. Maruse, "Bias Characteristics of the Hot Cathode Electron Microscope Gun" in Sixth International Congress for Electron Microscopy, Maruzen Co., Ltd., 1966, pp. 133-134.

46) B.N. Vasichev, G.V. Der-Shvarts, G.G. Larichev and V.P. Rachkov, "Illuminating System for a Combined X-Ray Microanalyzer and Electron Microscope", Instruments and Experimental Techniques 6, 1468 (1966).

47) V.E. Cosslett and M.E. Haine, "The Tungsten Point Cathode as an Electron Source", Proc. Third International Conf. on Electron Microscopy, London, 1956, pp. 639-644.

48) V.E. Cosslett, "Comparison of the Practical Limits of X-Ray and Electron Microscopy", Proc. Third International Conf. on Electron Microscopy, London, 1956, pp. 311-317.

49) V.E. Cosslett and W.C. Nixon, "The X-Ray Shadow Microscope", J. Appl. Phys. 24, 616 (1953).

50) H.H. Pattee, Jr., "Design of a Field-Emission X-Ray Tube" in X-Ray Microscopy and Microradiography, V.E.Cosslett, Editor, Academic Press, 1957, pp. 278-286.

51) L. Marton, R.A. Schrack and R.B. Placious, "A Field Emitter Point Projection X-Ray Microscope" in X-Ray Microscopy and Microradiography, V.E. Cosslett, Editor, Academic Press, 1957, 287-292.

52) V.E. Cosslett, W.C. Nixon and H.E. Pearson, "Improvements in the Point Projection X-Ray Microscope" in X-Ray Microscopy and Microradiology, V.E. Cosslett, Editor, Academic Press, 1957, pp.96-105.

53) B.W. Schumacher, "A Review of the (Macroscopic) Laws for the Electron Penetration Through Matter", in First International Conf. on Electron and Ion Beam Science and Technology, R. Bakish, Editor, Wiley, 1965, pp. 5-70.

54) T.P. Lin, "Estimation of Temperature Rise in Electron Beam Heating of Thin Films", IBM Journal 11, 527 (1967).

55) O.C. Wells, "Calculation of the Heat-Affected Zone During Pulsed Electron-Beam machining", IEEE Trans. Electron Devices 12, 224 (1965).

56) A. Vine and P.A. Einstein, "Heating Effect of an Electron Beam Impinging on a Solid Surface, Allowing for Penetration", Proc. IEE 111, 921 (1964).

57) L.G. Pittaway, "The Temperature Distributions in Thin Foil and Semi-Infinite Targets Bombarded by an Electron Beam", Brit. J. Appl. Phys. 15, 967 (1964).

58) H. Bruining, Physics and Applications of Secondary Electron Emission, Pergamon Press, 1954.

59) M. Kaminsky, Atomic and Ionic Impact Phenomena on Metal Surfaces, Academic Press Inc., 1965.

60) M.D. Hare, "The Stable Potential Attained by an Essentially-Floating Electron Emitter Bombarded by Electrons", 20th Physical Electronics Conf., M.I.T., 1960.

61) E.J. Sternglass, "Backscattering of Kilovolt Electrons from Solids", Phys. Rev. 95, 345 (1954).

62) H. Kanter, "Energy Dissipation and Secondary Electron Emission in Solids", Phys. Rev. 121, 677 (1961).

63) M.K. Testerman, R.W. Raible, B.E. Gilliland, J.R. Williams and G.B. Grimes, "Cold Electron Sources for Mass Spectrometric Applications", J. Appl. Phys. 36, 2939 (1965).

64) R.W. Raible, B.E. Gilliland and W.G. Hinson, "Emission Regulation of Cold-Electron Sources", J. Appl. Phys. 38, 890 (1967).

65) C.N. Burrous, A.J. Lieber and V.T. Zaviantseff, "Detection Efficiency of a Continuous Channel Electron Multiplier for Positive Ions", Rev. Sci. Instr. 38, 1477 (1967).

66) K.A. Hughes, D.V. Sulway, R.C. Wayte and P.R. Thornton, "Application of Secondary-Electron Channel Multipliers to Scanning Electron Microscopy", J. Appl. Phys. 38, 4922 (1967).

67) K.C. Schmidt and C.F. Hendee, "Continuous Channel Electron Multiplier Operated in the Pulse Saturated Mode", IEEE Trans. Nucl. Sci. 13, 100 (1967).

68) J. Adams and B.W. Manley, "The Channel Electron Multiplier, a New Radiation Detector", Philips Technical Rev. 28, 156 (1967).

69) R.F. Goff and C.F. Hendee, "Studies of the Secondary Electron Emission Yield, Energy and Angular Distribution from High Resistance Targets at Grazing Angles of Incidence", 27th Annual Conference on Physical Electronics, M.I.T., 1967.

70) J. Dimeff, A.J. Lieber and C.N. Burrous, "Average Charge Detector for Mass Spectrometers", Rev. Sci. Instr. 37, 1562 (1966).

71) J. Adams and B.W. Manley, "The Mechanism of Channel Electron Multiplication", IEEE Trans. Nucl. Sci. 13, 88 (1966).

72) D.G. Smith, "Gain Variations in Some Channel Multipliers", J. Sci. Instr. 43, 270 (1966).

73) D.A. Bryant and A.D. Johnstone, "Gain of a Channel Multiplier", Rev. Sci. Instr. 36, 1662 (1965).

74) J. Adams and B.W. Manley, "The Channel Electron Multiplier", Electron. Eng. 37, 180 (1965).

75) D.S. Evans, "Low Energy Charged-Particle Detection Using the Continuous-Channel Electron Multiplier",Rev. Sci. Instr. 36, 375 (1965).

76) G.W. Goodrich and W.C. Wiley, "Continuous Channel Electron Multiplier", Rev. Sci. Instr. 33, 761 (1962).